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TECHNICAL NOTE 4011

SOME ASPECTS OF FAIL-SAFE DESIGN OF PRESSURIZED FUSELAGES

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SUMMARY

Separate investigations have dealt with the critical crack length of flat sheets or of unstiffened cylinders and with the type of rupture experienced by stiffened cylinders. These investigations are correlated, supplemented by new tests, and combined into a uniform scheme for predicting critical crack length and type of rupture in stiffened pressurized cylinders.

INTRODUCTION

The fail-safe design of pressurized fuselages is a problem that has attracted much attention in the past few years. This paper is a progress report on work in this field and an attempt to correlate several lines of investigation.

SYMBOLS

A_{NET}	net area, sq in.
A_R	ring area (cross sectional), sq in.
K_u	stress-concentration factor at ultimate load for flat sheet
$K_{u,CYL}$	stress-concentration factor at ultimate load for cylinder
l	ring spacing, in.
P	load, kips
r	radius of cylinder, in.
t_s	skin thickness, in.

δ	length of slit or crack, in.
σ	stress, ksi
σ_{MAX}	maximum stress, ksi
σ_u	ultimate tensile stress, ksi

DEFINITIONS

The problem is defined in a general way by two questions: If initial damage, such as a fatigue crack, is inflicted on a pressurized stiffened shell, how large can the damage be before the pressure causes a rupture of the shell, and what is the nature of the rupture? The only type of initial damage considered here is a longitudinal crack or slit of length δ as shown in figure 1. (For aluminum alloys, to which this discussion is confined, the difference between a fatigue crack and a fine slit is negligible.) For any specified pressure or hoop tension, a critical length of crack exists at which the pressure will rupture the skin. The term "confined rupture" in this paper will refer to a rupture which stops at the nearest rings, as indicated on the sketch at the left. The term "unconfined rupture" will refer to a rupture which extends into adjacent bays, as indicated on the sketch at the right. An unconfined rupture of the skin often results in failure of the rings and sometimes of the stringers.

SURVEY OF PREVIOUS INVESTIGATIONS

Critical Crack Length

Figure 2 shows schematically the first two steps in the investigation of critical crack length. At the top is shown a flat sheet under tension with a central crack of length δ . When the maximum stress σ_{MAX} in the sheet at the two ends of the crack becomes equal to the tensile strength of the material, the sheet will tear apart. At this instant, the maximum stress is equal to the product of the net-section stress P/A_{NET} and a stress-concentration factor K_u .

A method for calculating the factor K_u has been published in reference 1. The calculation involves the stress-strain curve and a size-effect constant which is determined from a tension test on a specimen with a sharp notch of known radius. The presence of this size effect

in problems involving cracks or sharp notches invalidates the mechanical law of similarity that geometrically similar structures fail at the same stress and makes it impossible to draw generalized curves based on dimensionless parameters.

The lower sketch in figure 2 shows a pressurized unstiffened cylinder with a longitudinal crack. The stress-concentration factor for such a cylinder is calculated by the formula shown. The quantity K_u is the stress-concentration factor calculated for the configuration obtained by unwrapping the cylinder into a plane. The term in parentheses is the "curvature correction," which was found empirically and applies to 2024-T3 aluminum alloy as well as 7075-T6 aluminum alloy. The experimental basis for the formula may be found in reference 2.

The importance of the curvature correction is shown in figure 3. For the two aluminum alloys, the critical crack length is shown as function of the tensile stress for flat sheet and for cylinders with a radius of 15 inches, which is a widely used size representing roughly a 1/4-scale model of a fuselage. For all but very short cracks, the drop in strength due to curvature effect is obviously substantial. Curves of critical crack lengths of unstiffened cylinders corresponding to the curves shown in figure 3 will be used later as a yardstick or reference basis for stiffened cylinders.

Type of Rupture

The initial investigation of the problem of type of rupture was conducted on cylinders with radii of 15 or 24 inches, stiffened by stringers and riveted-on rings. Subjecting these cylinders to a constant internal pressure and to repeated torsion loads resulted in fatigue cracks at 45° to the cylinder axis.

Figure 4 shows the results of the initial investigation on 2024-T3 cylinders. Hoop stress is plotted as the ordinate and ring-reinforcement ratio, the ratio of the cross-sectional area of a ring A_R to the area of the associated skin lt_s , is plotted as the abscissa. The dashed line, labeled "theoretical criterion," is based on elementary considerations and gives the area which the rings must have to carry the hoop load if the skin itself cannot carry it because it is cracked or cut. The circles denote confined ruptures, the x-marks denote unconfined ruptures in the tests. The solid line, labeled "empirical criterion," is approximately the upper boundary of the confined ruptures. The ring-size criterion can thus be used as a basis for predicting the type of rupture. The data are taken from reference 3, except that the curve showing the empirical criterion is drawn here in a somewhat more conservative fashion than in the reference.

A few tests of the same nature have been made on cylinders of 7075-T6 material. The number of tests was too small to establish an empirical criterion for ring size, and the method of testing, pressure combined with cyclic torsion, has been replaced by pressure cycling.

NEW INVESTIGATIONS

Presented herewith are evaluations of more recent data. The presentation is aimed at answering two questions:

- (1) What correlation exists between the critical crack length for unstiffened cylinders and that for stiffened cylinders?
- (2) How reliable is the ring-size criterion for predicting the nature of the rupture of stiffened cylinders when the cracks are longitudinal rather than at 45° , as in the original investigation?

The majority of the tests discussed were actually made to obtain some preliminary information on the effect of parameters not considered previously, for instance, type of rings used. As a result, the tests available at this time are inadequate for giving definite answers to the two questions posed, but they do indicate trends.

The tests fall into three groups according to size of cylinder: small cylinders with a radius of 3.6 inches; medium-size ones with a radius of 15 inches; and full-scale ones with a radius of about 70 inches. All were stiffened by stringers and rings or hoops.

The small cylinders had precut slits and were brought to rupture by increasing the pressure steadily. The crack-length results are shown in figure 5. The curve, labeled δ_{REF} , gives the critical crack length of unstiffened cylinders having the same radius. The circles denote again confined ruptures; the x-marks, unconfined ruptures. Regardless of the type of rupture, all the critical crack lengths plot fairly close to the reference curve, which means that the critical crack lengths of the stiffened cylinders in this group of tests are equal to those of corresponding unstiffened cylinders.

Figure 6 shows the ring-size criterion plot for the same group of tests. Each test point represents the same specimen as the point at the same stress level in figure 5. The empirical criterion line is taken from figure 4. All ruptures observed are in agreement with the criterion: unconfined if above the curve, confined if below the curve. The cylinders in this test group had either rather light rings or else rather heavy rings; as a result this test group does not give a sensitive check on the

accuracy of the ring-size criterion. On the other hand, the fact that rather extreme ring sizes were used tends to increase the weight of the evidence regarding crack length shown in figure 5.

The next group of tests is on medium-size cylinders (15-inch radius) of 2024-T3 material. On these cylinders, the internal pressure was cycled to grow a fatigue crack, starting from an initial slit. Figure 7 shows the crack-length plot. The critical crack lengths for this group of tests are consistently longer than indicated by the reference curve, the excess length varying roughly from 40 percent to 100 percent. The result thus differs markedly from that obtained on the small cylinders.

Figure 8 is the ring-size plot for the medium-size cylinders. The types of failure are in agreement with the prediction, if the prediction for the border-line case on the line is made conservatively. This plot shows only 3 points, and thus no counterparts are shown for many of the points shown in figure 7; the missing points are discussed in the following paragraph.

On the small cylinders, and on the three medium-size cylinders discussed in the previous paragraph, the rings were riveted continuously to the skin. On the other medium-size cylinders, the rings were either floating, that is, not touching the skin at all, or they were touching the skin, but riveted to it only at the intersections with the stringers. Rings of either type are believed to have little if any power to confine rupture; therefore, the assumption is made that the presence of either type of ring justifies a prediction of unconfined rupture, and consequently, it is unnecessary to plot the point on the ring-criterion plot in order to arrive at a prediction of the type of rupture. So far, there appears to be no evidence that the assumption is unduly conservative.

Figure 9 shows the crack-length results for medium-size cylinders of 7075-T6. All the points plot close to the reference curve. Since the corresponding plot for 2024-T3 material (fig. 7) showed excess crack lengths ranging from 40 percent to 100 percent, it may be said that 2024-T3 has a "hidden margin of safety," under some conditions, which appears to be lacking in 7075-T6 material.

Figure 10 is the ring-size plot for the 7075-T6 cylinders. Only the theoretical criterion is shown, since no empirical criterion is established, as mentioned previously. The type of rupture is as expected in all cases, but the location of the points is such that the empirical criterion still remains undefined.

Figure 11 with data taken from references 4 and 5 shows two tests made by two aircraft manufacturers on full-scale models of fuselages with a radius of about 70 inches. The critical crack length is just above the

reference value for specimen A and about 60 percent larger for specimen B. This scatter suggests a scatter band somewhat similar to that obtained on the medium-size cylinders.

In specimen A, a saw slit had been made through the skin as well as through the ring underneath it. With one ring thus out of action, the ring-reinforcement ratio was marginal, which would lead to the prediction that the rupture will probably be unconfined. For specimen B, an unconfined rupture would be predicted because the rings were floating. The symbols indicate that both specimens had unconfined ruptures. It should be noted that both specimens served as starting points in the development of final designs.

CONCLUDING REMARKS

The crack-length criterion and the ring-size criterion appear to offer some promise as tools for putting some aspects of fail-safe design on a quantitative basis. The crack-length criterion in its present form states that the critical crack length of a stiffened cylinder is at least equal to that of an unstiffened cylinder of the same radius. The ring-size criterion, which is reasonably well established for 2024-T3 aluminum alloy but not for 7075-T6 aluminum alloy, appears to permit a prediction whether the rupture will be confined or unconfined when the rings are continuously riveted to the skin. When the rings are not so riveted (or otherwise fastened), the rupture will probably be unconfined.

Much work remains to be done, however. The conditions under which the critical crack length of the stiffened cylinder can be greater than that of the unstiffened cylinder should be established more fully. Only stray bits of information are available at present on a number of factors, such as effect of stringers, of load-carrying members bridging a crack, and of producing the initial damage very rapidly.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 6, 1957.

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2. Peters, Roger W., and Kuhn, Paul: Bursting Strength of Unstiffened Pressure Cylinders With Slits. NACA TN 3993, 1957.
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4. Sorensen, Arne: Some Design Considerations for Tear-Resistant Airplane Structures. Preprint No. 618, S.M.F. Fund Preprint, Inst. Aero. Sci., Jan. 1956.
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TYPES OF RUPTURE

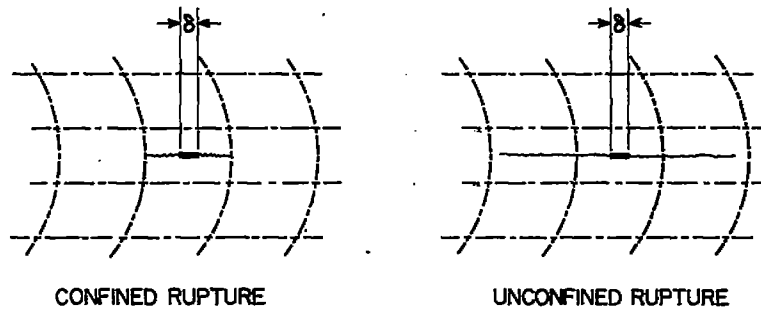


Figure 1

STRENGTH OF CRACKED SPECIMENS

$$\sigma_{MAX} = \frac{P}{A_{NET}} K_U = \sigma_U$$



$$K_{U,CYL} = K_U \left(1 + 4.6 \frac{s}{r} \right)$$

FOR 2024-T3 AND 7075-T6
ALUMINUM ALLOY

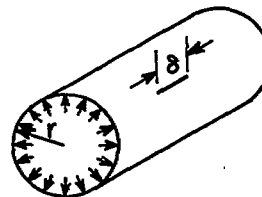


Figure 2

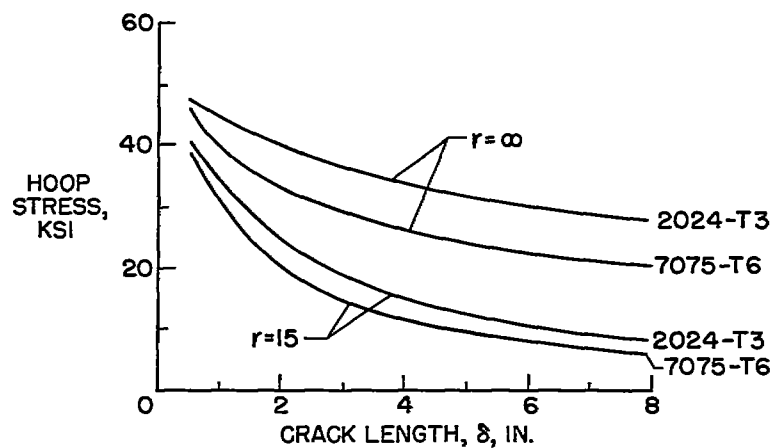
CRITICAL CRACK LENGTHS
UNSTIFFENED CYLINDERS

Figure 3

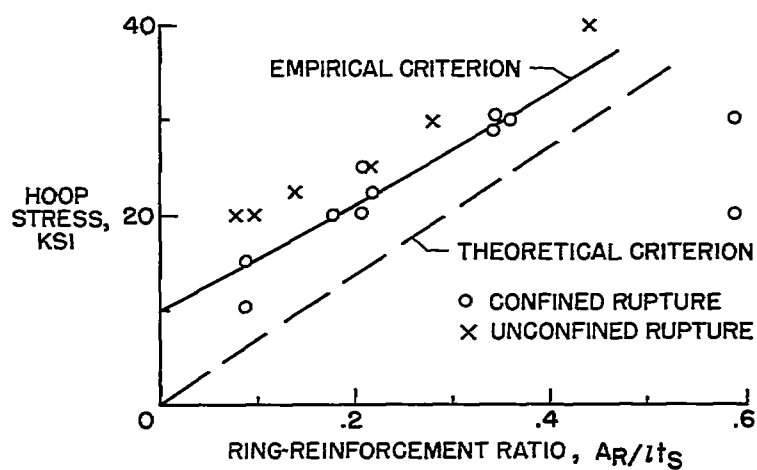
RING-SIZE CRITERION FOR 2024-T3
 $r=15$ AND 24 IN.; PRESSURE AND TORSION

Figure 4

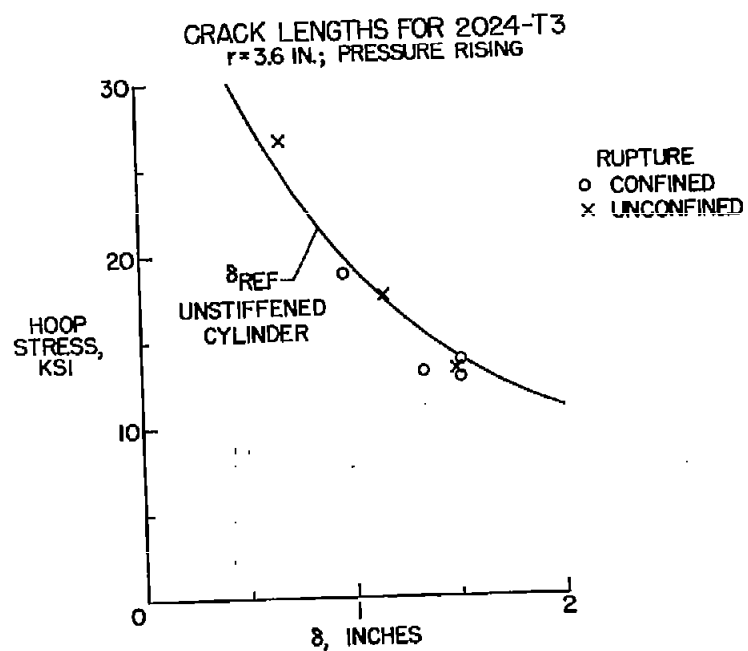


Figure 5

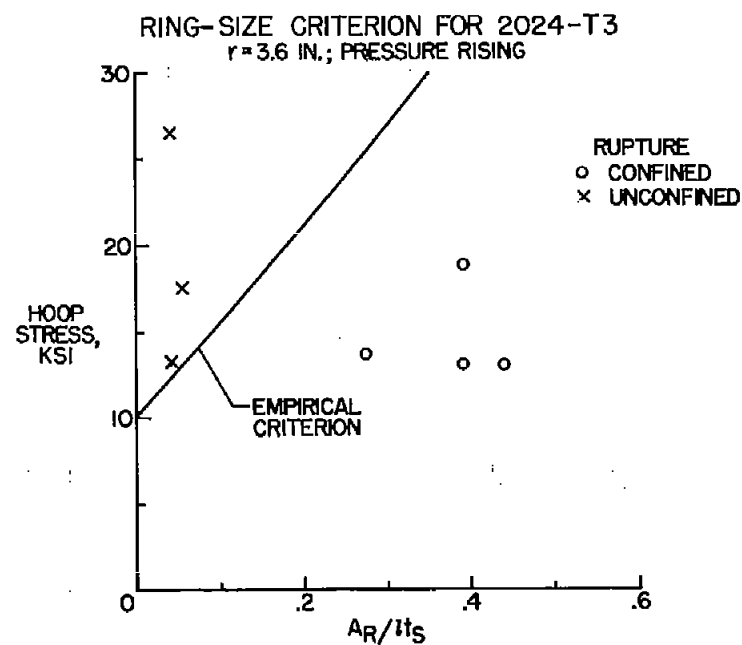


Figure 6

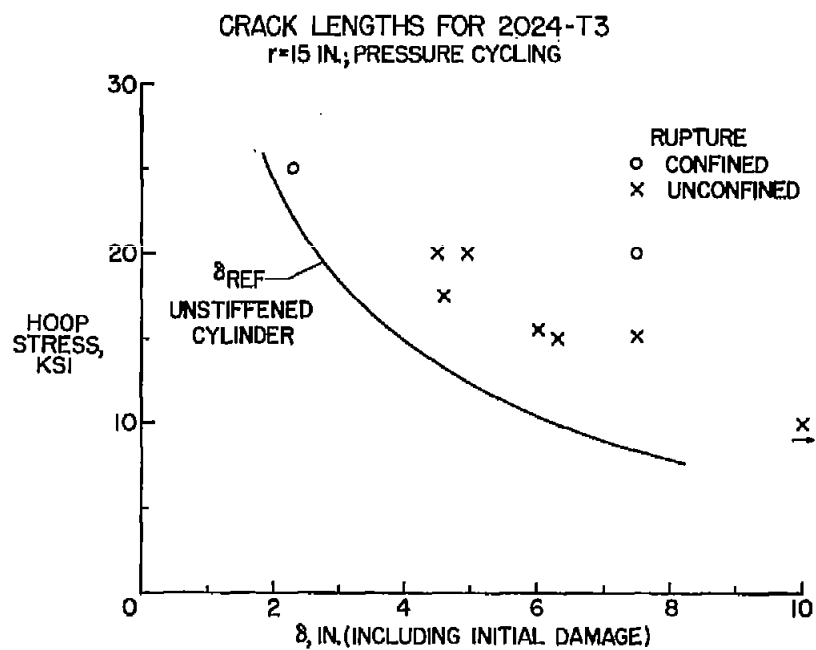


Figure 7

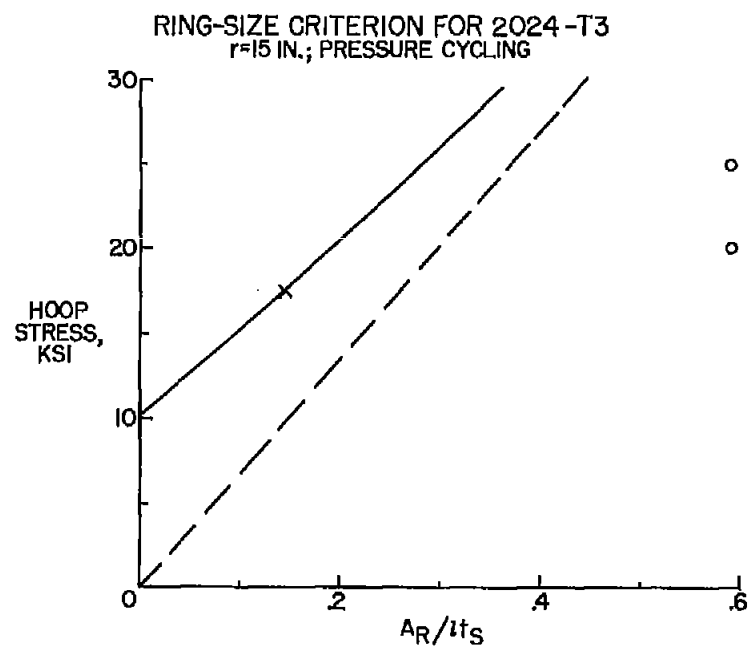


Figure 8

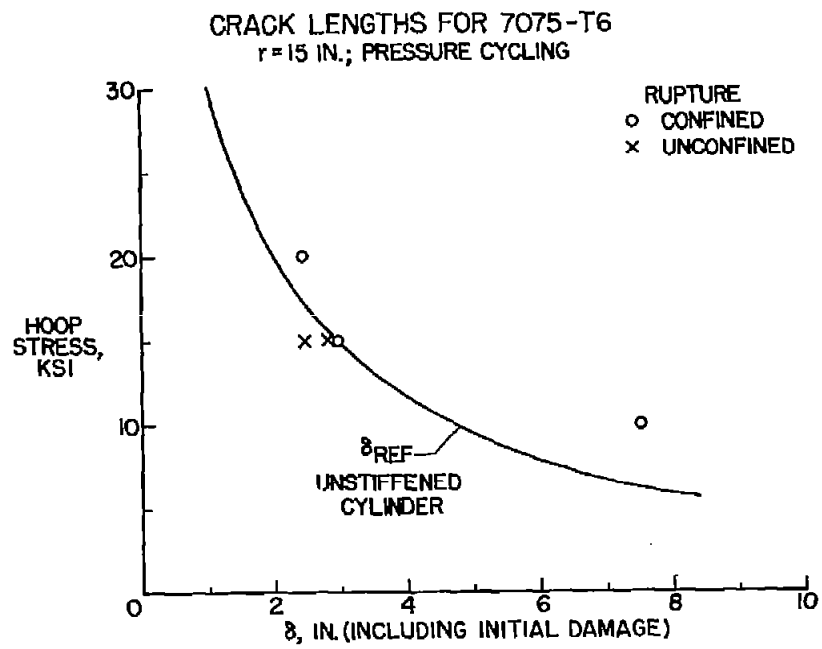


Figure 9

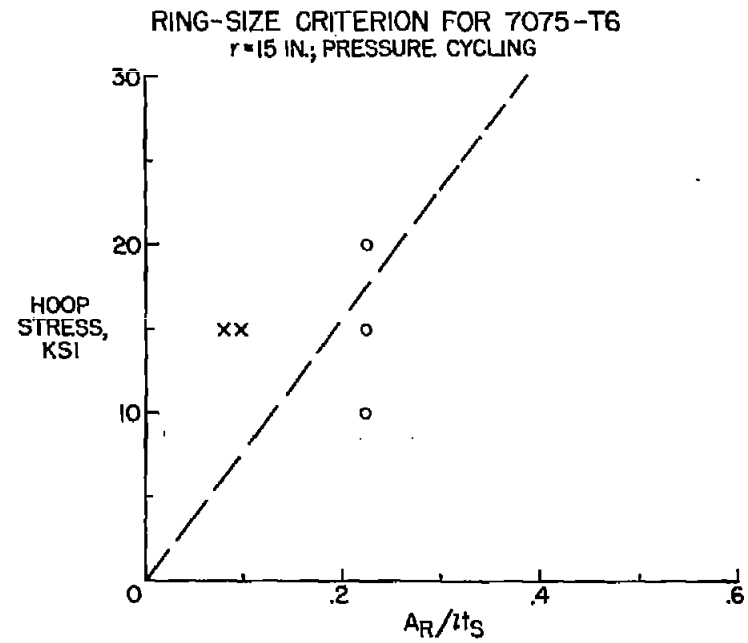


Figure 10

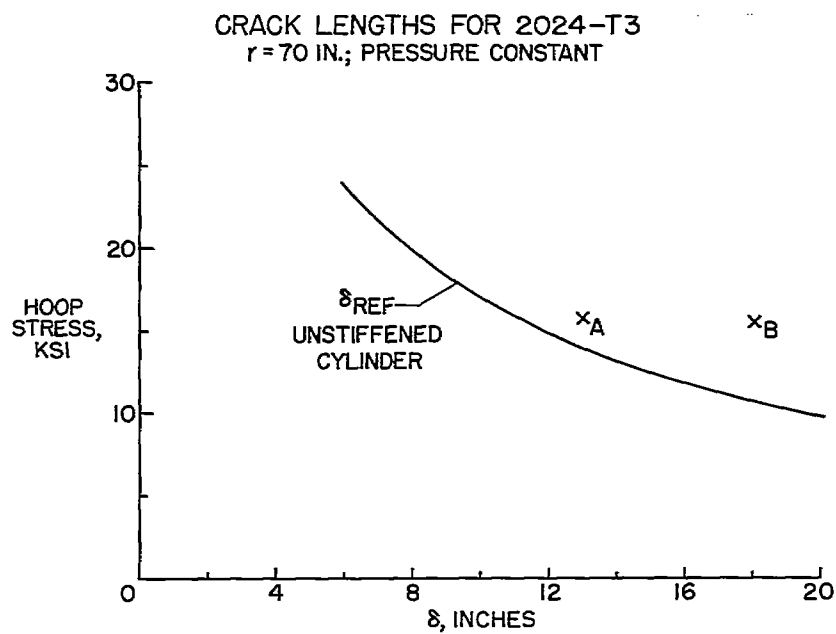


Figure 11